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FOR

OPTICAL MODULATOR

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OPTICAL MODULATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of the filing date of U.S. provisional application no. 60/448,735, filed on 02/20/2003.

5 BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates generally to the field of optical telecommunications, and in particular, to return-to-zero (RZ) modulators in optical transmitters.

Description of the Related Art

10 In the field of optical communications, RZ formats are often preferred over non-return-to-zero (NRZ) formats due to their increased robustness to a variety of distortions that are typically encountered in optical fiber propagation and in filtering and reception.

 The most commonly employed RZ transmitter structures make use of an NRZ data modulator either in combination with a sinusoidally driven intensity modulator acting as a pulse
15 carver, or in combination with an actively mode-locked laser. Efforts to reduce RZ transmitter complexity have led to designs that (i) use a single electro-optic modulator fed by an electrical RZ signal, (ii) employ an NRZ-driven phase modulator followed by a passive optical delay interferometer, or (iii) drive a Mach-Zehnder intensity modulator between its transmission minima with an NRZ signal to generate RZ pulses upon level changes in the NRZ drive signal.

20 More information on designs (i), (ii), and (iii) can be found in: N. M. Froberg et al., "Generation of 12.5 Gbit/s soliton data stream with an integrated laser-modulator transmitter," Electron. Lett., vol. 30, 1880-1881 (1994); P. J. Winzer and J. Leuthold, "Return-to-Zero Modulator Using a Single NRZ Drive Signal and an Optical Delay Interferometer," Photon. Technol. Lett., vol. 13, 1298-1300 (2001) (herein "Winzer '01"); and J. J. Veselka et al., "A
25 soliton transmitter using a cw laser and an NRZ driven Mach-Zehnder modulator," Photon. Technol. Lett., vol. 8, 950-952 (1996), respectively, each incorporated herein by reference in its entirety.

 As the demand for more bandwidth grows, the market pressure to reduce the cost, size, and complexity of RZ transmitters increases.

30 SUMMARY OF THE INVENTION

 Problems in the prior art are addressed in accordance with principles of the present invention by a method and apparatus for optical return-to-zero (RZ) modulation that are based on a single Mach-Zehnder modulator driven by non-return-to-zero (NRZ) electrical control

signals. The method and apparatus allow for continuously electrically tunable duty cycles and lead to chirped-RZ formats. One embodiment, a “push-pull” operation, involves driving one control arm of the Mach-Zehnder with a differentially encoded version of an NRZ data stream and driving the other control arm with an inverted and time-delayed copy of the same differentially encoded data stream. Another embodiment, a “push-push” operation, involves driving one control arm of the Mach-Zehnder with a differentially encoded version of an NRZ data stream and driving the other control arm with a time-delayed but non-inverted copy of the same differentially encoded data stream. In one or more embodiments, the duty cycle of the RZ modulation is controlled via the selection of the time delay between the electrical signals that drive the two arms of the Mach-Zehnder.

In one embodiment, the present invention is an apparatus for generating a modulated optical signal. The apparatus includes a signal splitter adapted to receive and split an input data signal into first and second copies, a delay element adapted to receive and delay the first copy relative to the second copy, and an optical signal modulator adapted to modulate light fed to the modulator in accordance with first and second control signals based on the delayed first copy and the second copy, respectively, to generate the modulated optical signal.

In another embodiment, the present invention is a method for generating a modulated optical signal. The method involves splitting an input data signal into first and second copies, delaying the first copy relative to the second copy, and modulating light based on the delayed first copy and the second copy to generate the modulated optical signal.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

FIG. 1 depicts two different embodiments of a chirped-RZ transmitter according to the present invention.

FIG. 2 depicts exemplary waveforms for the intensity and phase of the signal out of the Mach-Zehnder modulator for the push-pull configuration (**FIG. 2(a)**) and the push-push configuration (**FIG. 2(b)**).

DETAILED DESCRIPTION

Reference herein to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase “in one

embodiment” in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

The Transmitters

5 **FIG. 1** depicts two different embodiments of a chirped-RZ transmitter according to the present invention. These embodiments represent modifications of duobinary and alternate-mark-inversion NRZ transmitters. For duobinary signaling, a phase change occurs whenever there is an odd number of '0's between two successive '1's, whereas for AMI the phase changes for each '1' (even for adjacent '1's), independent of the number of '0's in between. More
10 information on such transmitters can be found in T. Franck et al., “Duobinary transmitter with low intersymbol interference,” *Photon. Technol. Lett.*, vol. 10, 597-599 (1998) (herein “Franck ‘98”), incorporated herein by reference in its entirety.. As discussed in the following, each transmitter results in a modulated optical output signal that exhibits a unique set of characteristics.

Push-Pull

15 **FIG. 1(a)** depicts a “push-pull” embodiment of chirped-RZ (CRZ) transmitter **100**, as well as associated electrical and optical waveforms **102** and **104**, respectively, according to one embodiment of the present invention.

CRZ transmitter **100** includes (optional) differential encoder **106**, continuous-wave
20 (CW) laser **108**, dual-drive Mach-Zehnder modulator (MZM) **110**, non-inverting driver amplifier **112**, inverting driver amplifier **114**, and variable delay element **116** of delay τ .

Operationally, CW laser **108** feeds MZM **110** with an optical signal that is modulated by the MZM with a differentially encoded representation of an electrical NRZ data signal that has a bit period of T seconds. In particular, differential encoder **106** receives the electrical NRZ data
25 signal and translates it to a differentially encoded signal that is split into two paths. One path is fed to non-inverting driver amplifier **112**, which drives one electrical control arm of MZM **110**. The second path feeds delay element **116** where the signal is delayed by τ seconds, where $\tau \leq T$. The delayed signal out of the delay element is then fed to inverting driver amplifier **114**, which drives the other control arm of MZM **110**. Electrical waveforms **102** correspond to the
30 differentially encoded signal from driver amplifier **112** and the inverted, delayed, differentially encoded signal from driver amplifier **114**.

The differential encoder operates by translating each occurrence of a logical “1” in the electrical NRZ data signal into a level change on the encoder’s output. For example, an NRZ

data signal representing the bit pattern 1000111 would be encoded as SNNNSSS, where S denotes a level shift and N denotes no level shift. Such a differential encoding scheme is discussed in more detail in Franck '98. Note that it is not strictly necessary to precode the signals at the transmitter. In an alternative implementation, the differential encoder can be omitted, the MZM can be modulated with the uncoded NRZ data signal, and appropriate decoding can be done at the receiver, as would be understood by one skilled in the art. However, in practice, precoding at the transmitter leads to a more noise-tolerant system than performing decoding at the receiver.

Note that MZM 110 is biased for destructive interference in the absence of drive level changes between its control arms. Thus, the output power of the MZM in the absence of level transitions is essentially zero. However, as a result of changes in the control arm drive voltages (see, for example, waveforms 102) that result from logical ones in the electrical NRZ data signal, pulses are produced (e.g., pulses 118 of waveform 104) in the output of the MZM corresponding to where the interference properties of the MZM are altered by the two modulating electrical NRZ waveforms 102. The duration of each pulse (i.e., its pulsewidth) is determined by the electrical delay τ and the rise/fall times of the MZM control arm drive signals.

Push-Push

FIG. 1(b) depicts a "push-push" embodiment of chirped-RZ transmitter 120, as well as associated electrical and optical waveforms 122 and 124, respectively, according to another embodiment of the present invention.

CRZ transmitter 120 includes (optional) differential encoder 126, continuous-wave laser 128, dual-drive Mach-Zehnder modulator 130, non-inverting driver amplifiers 132 and 134, and delay element 136 of delay τ .

Operationally, it should be noted that corresponding elements of CRZ transmitter 120 behave similarly to those of CRZ transmitter 100. Namely, CW laser 128 feeds MZM 130 with an optical signal that is modulated by the MZM with a differentially encoded representation of an electrical NRZ data signal that has a bit period of T seconds. In particular, differential encoder 126 receives the electrical NRZ data signal and translates it to a differential signal, still in NRZ format. The resulting differentially encoded signal is split into two paths. One path is fed to non-inverting driver amplifier 132, which drives one electrical control arm of MZM 130. The second path feeds delay element 136 where the signal is delayed by τ seconds, where $\tau \leq T$. The delayed signal out of the delay element is then fed to non-inverting driver amplifier

134, which drives the other control arm of MZM 130. Electrical waveforms 122 correspond to the differentially encoded signal from driver amplifier 132 and the delayed, differentially encoded signal from driver amplifier 134.

MZM 130 is biased for destructive interference in the absence of drive level changes between its control arms. Thus, the output power of the MZM in the absence of level transitions is essentially zero. However, as a result of changes in the control arm drive voltages (see, for example, waveforms 122) that result from logical ones in the electrical NRZ data signal, pulses are produced (e.g., pulses 138 of waveform 124) in the output of the MZM corresponding to where the interference properties of the MZM are altered. The duration of each pulse (i.e., its pulsewidth) is determined by the electrical delay τ and the rise/fall times of the MZM control arm drive signals.

Pulsewidth and Waveform Characteristics

FIG. 2 depicts exemplary waveforms for the intensity and phase of the signal out of the MZM for the push-pull configuration (e.g., FIG. 2(a)) and the push-push configuration (e.g., FIG. 2(b)) for electrical delays of τ equal to T , $0.5 \cdot T$, and $0.1 \cdot T$. In each case, the electrical MZM control signal is assumed to have a 10% - 90% rise time of $0.4 \cdot T$, corresponding to a moderate drive bandwidth of $0.9 / T$. The drive levels of the control signals are chosen equal to the MZM's switching voltage V_π . This results in destructive interference at the output of the MZM under nominal circumstances (e.g., NRZ data = 0). As shown in FIG. 2, relatively short RZ pulses can be generated without the need for exceedingly high electrical-drive bandwidths.

One difference between the push-pull embodiment and the push-push embodiment is that the push-pull embodiment yields a substantially constant peak pulse power, independent of τ , while the peak pulse power decreases with τ in the push-push implementation. This is because, for push-pull operation, the drive-voltage difference $\Delta u(t) = u_1(t) - u_2(t)$ between the two MZM control arms, which is responsible for the optical power transmission of the MZM, always passes a transmission maximum at $\Delta u(t) = 0$ when switching between the transmission minima that are present at $\Delta u(t) = V_\pi - 0$ and $\Delta u(t) = 0 - V_\pi$ (i.e., the voltage differences associated with no control arm drive level changes).

For push-push operation, on the other hand, constructive interference in the MZM, leading to RZ-pulse peaks, is found at times of maximum drive voltage difference Δu . As can be seen from FIG. 1(b), this difference is reduced once τ falls short of the modulation rise

time. To avoid the excess modulation insertion loss introduced by this effect, the drive voltage can be increased. Conversely, in circumstances when a higher modulator insertion loss is acceptable, the push-push embodiment may be used for control arm drive voltages smaller than V_{π} , while the push-pull implementation involves drive levels substantially equal to V_{π} on both arms of the MZM, or degradations in extinction ratio will be encountered.

Regarding the phase of the optical pulses, **FIG. 2(a)** reveals that the push-pull implementation yields alternate-chirp RZ signals, with lower phase excursions at reduced duty cycles. Signals of this kind can offer potential advantages for non-linear fiber propagation as discussed in R. Ohhira, D. Ogasahara, and T. Ono, "Novel RZ signal format with alternate-chirp for suppression of nonlinear degradation in 40 Gb/s based WDM," Proc. OFC'01, paper WM2 (2001), incorporated herein by reference in its entirety.

The push-push implementation, on the other hand, in addition to a π -phase jump for every RZ pulse (see **FIG. 2(b)**), typically generates linear phase transitions of alternating sign over the pulse duration. In other words, it lets adjacent pulses experience opposite frequency shifts, as discussed in Winzer '01. In the limit as $\tau \rightarrow T$ and as the rise and fall times of the control arm drive signals approach zero, both embodiments of the present invention can produce unchirped, alternate-mark-inversion, NRZ signals out of the MZM.

Note that various alternative implementations may be substituted for the exemplary implementations illustrated in **FIGs. 1 (a)** and **1 (b)**. For example, a push-push implementation that replaces each non-inverting driver amplifier (**132** and **134**) in the embodiment of **FIG. 1(b)** with an inverting driver amplifier, two inverting driver amplifiers, or no driver amplifiers at all (assuming drive levels from the differential encoder were sufficient) would be within the spirit and scope of the present invention. Similarly, in the push-pull implementation of **FIG. 1(a)**, equivalent arrangements of driver amplifiers including swapping the location of inverting and non-inverting driver amplifiers (**114** and **112**), while making appropriate voltage offset adjustments, using no driver amplifier in place of non-inverting driver amplifier **112** while using inverting driver amplifier **114**, and other equivalent arrangements as would be understood by one skilled in the art, would remain within the scope and spirit of the present invention.

Also, a splitter, as described herein, should be understood to include any active or passive electronic device that produces two substantially identical or logically inverted copies of one data stream as would be understood to one skilled in the art. Similarly, the process of splitting should be understood to include any active or passive process that produces two substantially identical or logically inverted copies of one data stream.

Additionally, it should be noted that, in the push-pull embodiment of the present invention depicted in **FIG. 1 (a)**, the order of delay component **116** and inverting driver amplifier **114** may be reversed (i.e., the signal out of differential encoder **106** may be split and amplified, inverted, and then delayed before being fed to MZM **110**) while remaining within the scope of the present invention. Alternatively, driver amplifier **112** and inverting driver amplifier **114** can be deleted and a single dual-output (one output invert) driver amplifier can be inserted after differential encoder **106**. In this alternative arrangement, one output of the dual-output driver amplifier is fed to delay element **116**, which in turn feeds MZM **110** and the other output is fed to MZM **110** directly.

In a similar manner, in the push-push embodiment of the present invention depicted in **FIG. 1 (b)**, the order of delay component **136** and driver amplifier **134** may be reversed. Alternatively, driver amplifiers **132** and **134** can be deleted and a single dual-output driver amplifier can be inserted after differential encoder **126**. In this alternative arrangement, one output of the dual-output driver amplifier is fed to delay element **136**, which in turn feeds MZM **130** and the other output is fed MZM **130** directly. Alternatively, in the latter arrangement, the driver amplifier may be of the single output variety and a single output lead from the driver amplifier can be directly split or fed to a printed-circuit board trace that is then split between the delay element and the direct feed to the MZM. Other equivalent arrangements are within the scope and spirit of the present invention as would be understood to one skilled in the art.

Note that the elements of the present invention may be implemented by various techniques and in various technologies while remaining within the spirit and scope of the invention. These techniques and technologies include, but are not limited to, integrated optics (including silica on silicon substrate or Si:SiO₂), fiber optics, free space optics, thin film, InGaAs, InP, and LiNbO₃ subsystems.

Note that in one or more embodiments of the present invention, variable delay elements **116** and **136** of **FIGs. 1 (a)** and **1 (b)**, respectively, can be dynamically configured by an integrated or external controller (not illustrated).

While this invention has been described with reference to illustrative embodiments, this description should not be construed in a limiting sense. Various modifications of the described embodiments, as well as other embodiments of the invention, which are apparent to persons skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.